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Effect of velocity-dependent friction on multiple-vehicle collisions in traffic flow

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HIGHLIGHTS

- We presented the dynamic model of multiple-vehicle collisions to take into account the velocity-dependent friction force.
- We studied the effect of the velocity-dependent friction on the chain-reaction crash on a road.
- We explored the dependence of the multiple-vehicle collisions on the velocity-dependent friction.

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ABSTRACT

We present the dynamic model for the multiple-vehicle collisions to take into account the velocity-dependent friction force. We study the effect of the velocity-dependent friction on the chain-reaction crash on a road. In the traffic situation, drivers brake according to taillights of the forward vehicle and the friction force depends highly on the vehicular speed. The first crash may induce more collisions. We investigate whether or not the first collision induces the multiple-vehicle collisions, numerically and analytically. The dynamic transitions occur from no collisions, through a single collision and double collisions, to multiple collisions with decreasing the headway. We explore the effect of the velocity-dependent friction on the dynamic transitions and the region maps in the multiple-vehicle collisions.

1. Introduction

Mobility is nowadays one of the most significant ingredients of a modern society. The transportation problems have been studied from a point of view of statistical physics and nonlinear dynamics [1–5]. Vehicular traffic is a self-driven many-particle system of strongly interacting vehicles. Physicists have applied the concepts and techniques of physics to such complex systems as transportation systems [6–46].

Traffic accident prevents the traffic flow, blocks the highway, and induces severe congestions. Frequently, the collisions between vehicles happen by the blockage. Sometimes, the crash induces more collisions and results in the chain-reaction crash (multiple-vehicle collision). The multiple-vehicle collisions are a road traffic accident involving many vehicles. Generally occurring on high-capacity and high-speed routes such as freeways, they are one of the deadliest forms of traffic accidents. The most disastrous pile-ups have involved more than a hundred vehicles. The mass of crumpled vehicles depends greatly on the traffic situation, drivers, and vehicles.

The multiple-vehicle collisions have been studied by the use of physical models. Nagatani and Yonekura have investigated the multiple-vehicle collision induced by lane changing [47]. Also, the multiple-vehicle collision induced by a sudden slowdown has been investigated by Sugiyama and Nagatani [48]. The condition of the multiple-vehicle collision has been

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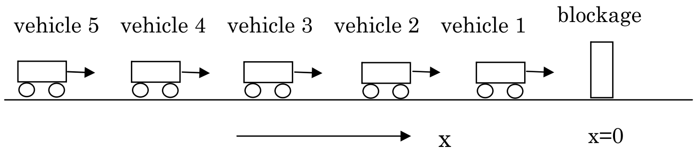

Fig. 1. Schematic illustration of the dynamic model for the traffic flow of vehicles with the velocity-dependent friction on the single-lane highway with the blockage. The vehicles are numbered from the downstream to the upstream. Successively, the taillights of vehicle n switch on at time $n\tau$.

explored by using the optimal velocity model. Frequently, the chain-reaction crash occurs in low-visibility conditions as drivers are sometimes caught out by driving too close to the vehicle in front and not adjusting to the road conditions. In low-visibility conditions, drivers brake to a stop as soon as the taillights of the forward vehicle switch on. The traffic flow in low visibility is controlled by the taillights. The traffic behavior in low-visibility conditions is definitely different from that in the normal conditions. The multiple-vehicle collision in low-visibility conditions has been investigated by using the friction-force model [49,50]. It has been classified how much speed and how long headway between the vehicles ahead or behind is necessary to avoid the multiple-vehicle collision.

In the friction-force model, the friction coefficient does not depend on the vehicular speed but is a constant. However, the friction force depends highly on the vehicular speed in real vehicles. In low speed, the brakes work but are hard to work in high speed. The velocity-dependent friction affects greatly the multiple-vehicle collisions. The effect of the velocity-dependent friction on the multiple-vehicle collisions has not been studied until now. It is not known how the velocity-dependent friction has an effect on the chain-reaction crash.

In this paper, we present the dynamic model for the multiple-vehicle collisions to take into account the velocity-dependent friction. We study the effect of the velocity-dependent friction upon the multiple-vehicle collisions on a highway in low visibility when the leading vehicle stops suddenly by a blockage. We investigate how the chain-reaction crash is affected by the velocity-dependent friction. In the vehicular traffic with the velocity-dependent friction, we derive a criterion that the braking vehicle comes into collision with the vehicles ahead and the crash induces more collisions. We study the dynamic transitions from no collisions to multiple-vehicle collision. We find the dependence of the mass of the crumpled vehicles on the velocity-dependent friction. We show the region map for the multiple-vehicle collisions analytically.

2. Model

In the situation that many vehicles move ahead on a single-lane highway with a blockage, we consider the process of multiple-vehicle collisions in low visibility. All vehicles move with the same headway b and speed v_0 before braking. The vehicles are numbered from the downstream to the upstream. The leading vehicle is numbered as one. The taillights switch on instantly when the vehicle brakes. There is a delay (perception-reaction time) τ until the vehicle brakes after the driver recognizes red taillights of the forward vehicle. The driver brakes to a stop after delay τ. Fig. 1 shows the schematic illustration of the dynamic model for the vehicular traffic controlled by the taillights on the single-lane highway with the blockage. The taillights of the leading vehicle switch on after time τ. Then, the taillights of the second vehicle switch on at time 2τ. Successively, the taillights of vehicle n switch on at time $n\tau$. The lighting taillights propagate backward (to the upstream) like red wave.

The total stopping distance consists of two principal components: one is the braking distance and the other is the reaction distance. The braking distance refers to the distance that a vehicle will travel from the point when the brakes work to the point when it comes to a complete stop. It is determined by the speed of the vehicle and the friction coefficient between the tires and the road surface. The reaction distance is the product of the speed and the perception-reaction time of the driver.

We take into account only the friction force for braking of the vehicular motion. The friction coefficient depends on the vehicular speed. The dynamics of braking is described by the following equation of motion of vehicle n:

$$M\frac{\mathrm{d}^2 x_n}{\mathrm{d}t^2} = -\mu\left(\frac{\mathrm{d}x_n}{\mathrm{d}t}\right)Mg, \tag{1}$$

where $x_n(t)$ is the position of vehicle n at time t, $\mu(\frac{\mathrm{d}x_n}{\mathrm{d}t})$ is the velocity-dependent friction coefficient, M is the mass of a vehicle, and g is gravitational acceleration. The friction coefficient μ is a function of velocity $\frac{\mathrm{d}x_n}{\mathrm{d}t}$. The first term on the right-hand side represents the friction force between the tires and the road surface.

In order to obtain the analytical solution, we consider the case that the friction coefficient decreases linearly with increasing speed for the velocity-dependent friction coefficient. The friction function is given by the following:

$$\mu\left(\frac{\mathrm{d}x_n}{\mathrm{d}t}\right) = \mu_0\left(1 - a\frac{\mathrm{d}x_n}{\mathrm{d}t}/v_{\max}\right), \tag{2}$$

where a defined [0, 1] is a proportional constant, μ_0 is the bare friction coefficient, and $v_{\max}$ is the maximal velocity. When a belongs to (0, 1], the friction force is velocity-dependent. When $a = 0$, the friction force is velocity-independent.